Integrated Lunar Transportation System

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An integrated transportation system is proposed from the lunar poles to Earth orbit, using solar-powered electric vehicles on lunar tramways, highways, and a lunar space elevator. The system could transport large amounts of lunar resources to Earth orbit for construction, radiation shielding, and propellant depots, and could supply lunar equatorial, polar, and mining bases with manufactured items. We present a system for lunar surface transport using "cars, trucks, and trains," and the infrastructure of "roads, highways, and tramways," connecting with the lunar space elevator for transport to Earth orbit. The Apollo Lunar Rovers demonstrated a battery-powered range of nearly 50 kilometers, but they also uncovered the problems of lunar dust. For building dustless highways, it appears particularly attractive to create paved roads by using microwaves to sinter lunar dust into a hard surface. For tramways, tall towers can support high-strength ribbons that carry cable cars over the lunar craters; the ribbon might even be fabricated from lunar materials. We address the power and energy storage requirements for lunar transportation vehicles, the design and effectiveness of lunar tramways, and the materials requirements for the support ribbons of lunar tramways and lunar space elevators.

1. Introduction

NASA is implementing a plan for a return to the Moon, which will build on and expand the capabilities demonstrated during the Apollo landings. The plan includes long-duration lunar stays, lunar outposts and bases, and exploitation of lunar resources on the Moon and in Earth orbit[1]. Because there are apparently deposits of water ice in shadowed craters near the lunar poles, and extensive areas of lunar regolith deposits of useful minerals in the lunar maria nearer the lunar equator, it will be necessary to create an integrated lunar transportation system to connect these locations with each other and with locations in Earth orbit. Because of the large delta-V requirements for carrying rocket fuel from the Earth's surface all the way to the Moon, we examined alternative transportation systems that do not use rockets, but do use indigenous lunar materials. The system we propose here is based on presentations at the Rutgers Lunar Settlements Symposium in 2007[2], the Moonbase conference in Venice, Italy in 2005[3] and the final report of a study for NIAC in 2005[4].

The integrated lunar transportation system consists of a lunar space elevator (LSE) balanced about the L1 Lagrangian point and extending directly down to the lunar equator; an elevated tramway, using the same composite ribbon as the space elevator, extending to the lunar south pole; and robotic vehicles that move along this transportation system by solar power and efficient

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energy storage to operate through the lunar night. As part of the process of building the tramway suspended on towers located on mountain tops and crater rims, highways can also be created for robotic vehicles (and perhaps even manned vehicles) to move the 2700 km between the lunar equator and the poles. The integrated transportation system is shown schematically in Figure 1.

This system is designed to transport lunar polar ice over the tramway, up the space elevator, and from there into high Earth orbit, where it can be used for refueling hydrogen/oxygen rocket engines for launches to all over the solar system. The flow in the opposite direction will be supplies and manufactured goods from Earth orbit to the lunar bases and the polar mining stations. The components of the system are described in the following sections.

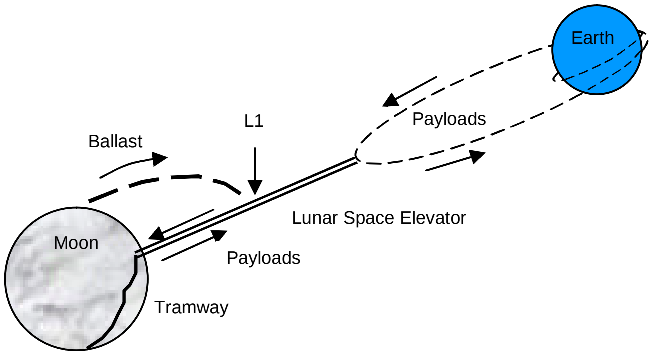


Figure 1. Integrated Lunar Transportation System

2. System Description

The key component of the system is the lunar space elevator, shown in Figure 2, first published by Pearson[5,6] in 1977 and independently by Artsutanov[7] in 1979. (Tsander, the Russian visionary, looked at a lunar space elevator even earlier[8].) The LSE is an extension of the concept of the Earth space elevator, invented by Artsutanov[9] (1960) and independently by Pearson[10] (1975).

The classical Earth space elevator is essentially a geostationary satellite that is elongated until the lower end touches the Earth at the equator, and the upper end extends to an arbitrary distance and ends in a counterweight that keeps the entire structure in balance about the geostationary orbit altitude. Unfortunately, the Earth space elevator requires materials as strong as carbon nanotubes, because of the Earth's high gravitational field. The lunar space elevator can be constructed from current composite materials, but it is more complicated to analyze, because it can only be balanced about the L1 or L2 unstable Lagrangian points of the Earth-Moon-spacecraft three-body system. These points are about one-sixth of the Earth-Moon distance from the lunar surface. The lunar transportation system uses the L1 lunar space elevator with ribbons of available high-strength composites. As shown in the figure, the lunar space elevator could be curved to touch down at points other than the lunar equator.

Figure 3 shows an artist's concept of the transportation system for carrying payloads of water from the lunar poles to the lunar space elevator, and from there to Earth orbit. Robotic vehicles with electric motors powered by large solar arrays and energy storage, like the one shown here,

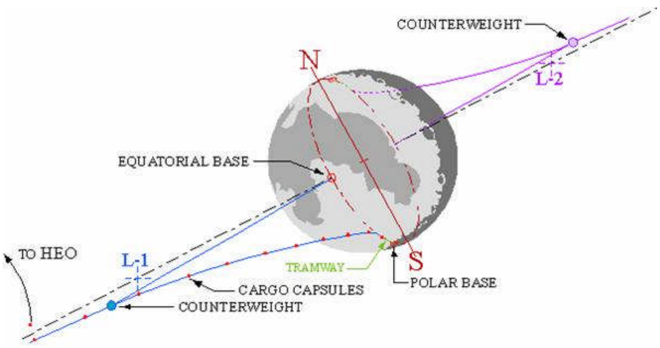


Figure 2. Lunar Space Elevators

would move from the pole along the tramway, climb up the LSE, be released at the top, and continue to Earth orbit using electric propulsion. The vehicles could drop lunar resources in Earth orbit, pick up supplies for the lunar polar station, and return by rendezvous with the top of the elevator and continuing down to the tramway.

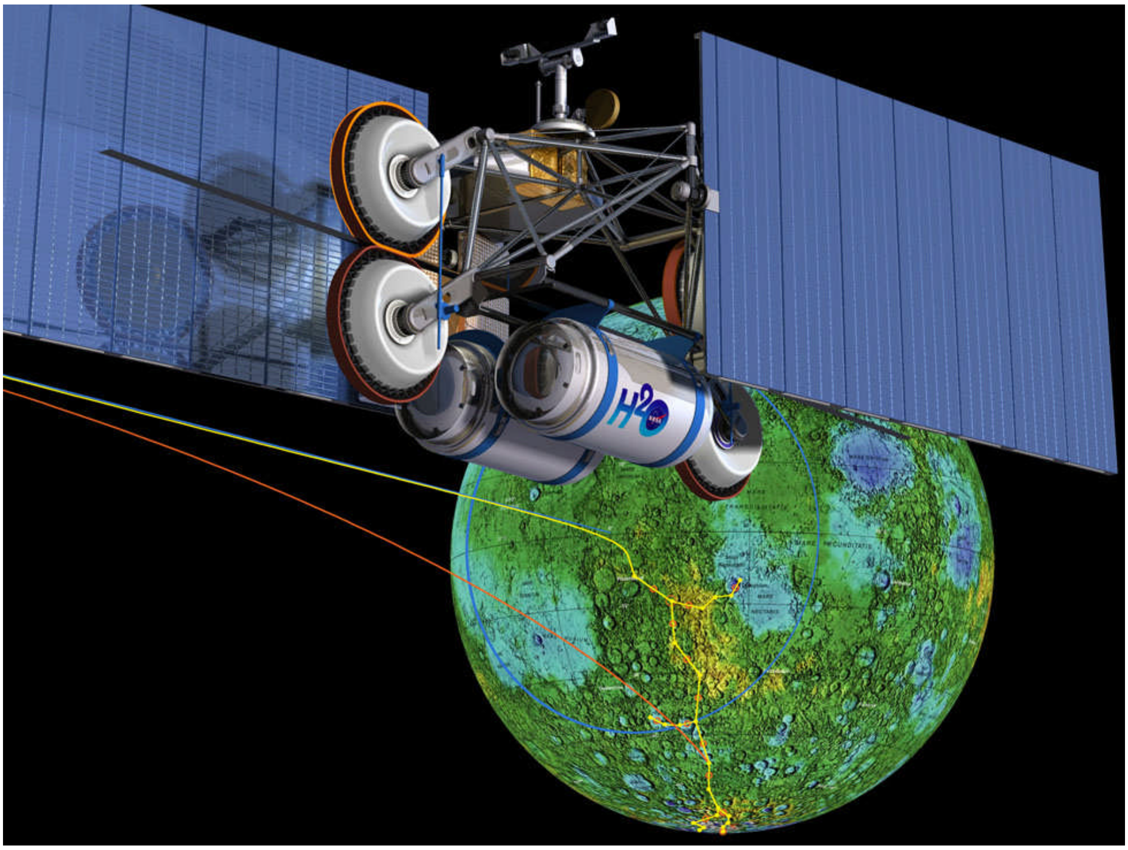


Figure 3. The Lunar Space Elevator and Tramway System

The second major element of the system is the lunar tramway connecting the base of the LSE on the equator with the ice mines at the poles. The lunar tramway is envisioned to run over 2700 km from the equator to the poles, connecting various maria mineral deposits and regolith mining sites as well as the water ice mines at the south pole. There may be ice deposits at the north pole as well, and a second tramway could be constructed in that direction.

The tramway needs to be constructed of the same high-strength composite ribbons as the space elevator, suspended from towers located on lunar mountains and crater rims. The high strength allows long spans of scores to hundreds of kilometers, minimizing the number of support towers required. For maximum span, the support towers could be located on the rims of craters and on the tops of mountains. The tramway system is shown schematically in Figure 4, with spans extending up to scores of kilometers between towers in the low lunar gravity field.

The tramway terminates at the lunar polar mining camp, where the same kind of high-strength ribbons can support mining rigs suspended over shadowed polar craters, as sketched in Figure 5. The water is mined in the crater at a temperature of less than 100K (~10^{-9} Torr), and is transported at a temperature of about 270K (~ 2 Torr). Such a facility, powered by 110 kW of continuous power from a nearby sunlit area covered with solar cells, could collect about 200,000 kg of water per year. This would compose the bulk of the cargo carried by the tramway capsules to the lunar space elevator and on to Earth orbit.

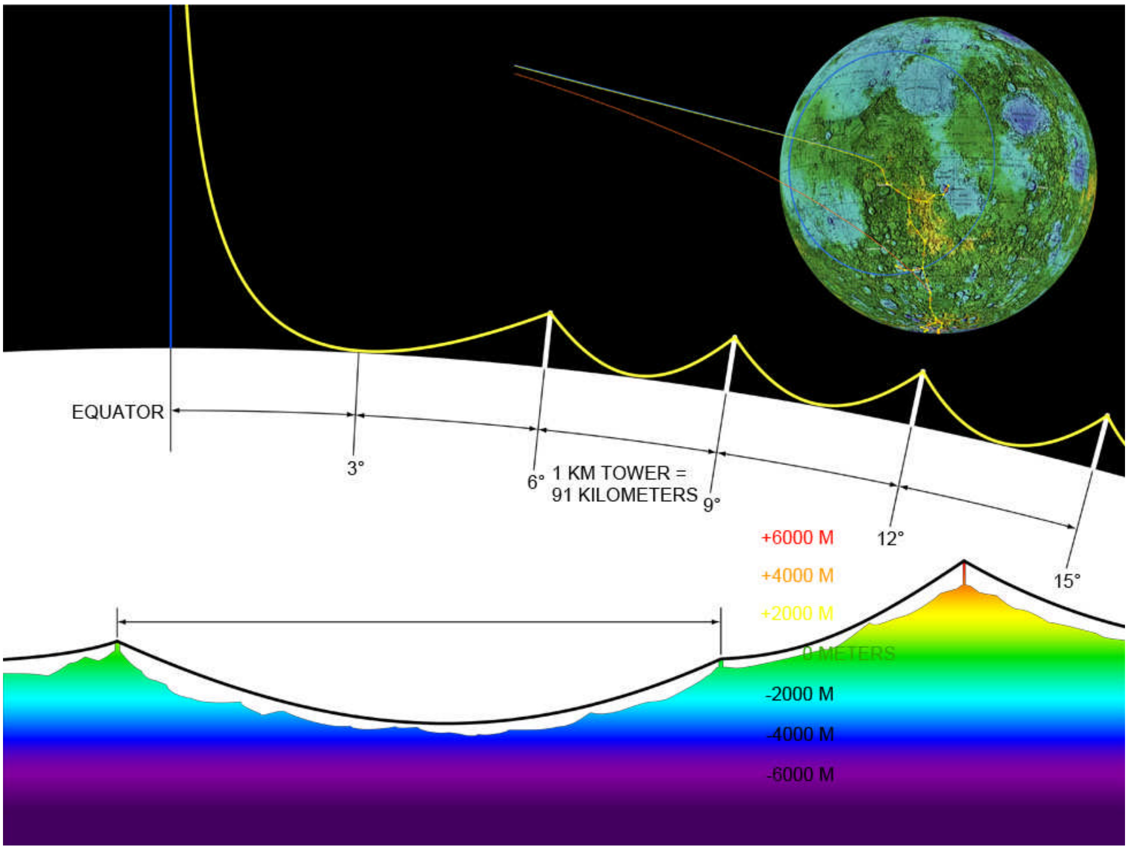
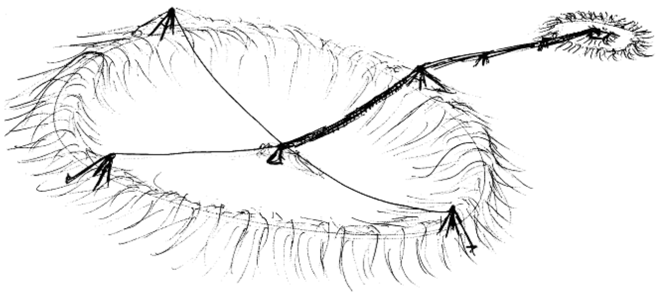


Figure 4. The Lunar Tramway Extends from Equator to Pole

Figure 5. *In-Situ* Lunar Resource Mining at a Polar Crater



The next sections discuss these components of the integrated transportation system in more detail, and provide some numbers on the system design parameters and operation.

3. The Lunar Space Elevator Component

Lunar and Mars space elevators are much easier than Earth space elevators, as shown in Figure 6. The basic parameter is the specific strength of the material, h = $\sigma \cdot \rho / g_0$, the limiting stress times the density divided by Earth's gravity. The term h has the dimensions of length (the longest cable that can be suspended in 1 g), and has been called the "characteristic height," or "breaking height." Typical metals like aluminum and steel have h = 10-50 km, high-strength composites like M5 are about 500 km, and carbon nanotubes are about 2200 km. The design parameter for a space elevator is the area taper ratio in cross-sectional area from the maximum at the balance point to the minimum at the surface. The minimum cross-sectional area is determined by the required lifting capacity at the base, which is the stress limit divided by the area. The lunar space elevator has about 1% of the specific stress requirements of the Earth space elevator.

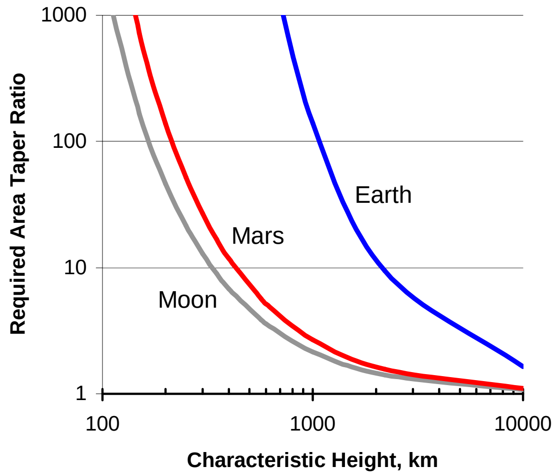


Figure 6. Space Elevator Taper Ratios

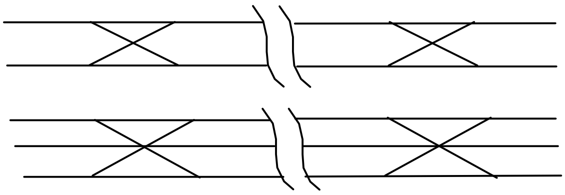
The space elevator must be constructed of extremely strong, lightweight materials, to support its weight over the tens of thousands of kilometers of length; even then, for minimum mass it must be tapered exponentially as a function of the planet's gravity field and the strength/density of the building material. The table below shows some candidate materials for lunar space elevators, with density, stress limit, and the breaking height. Lunar space elevators require much lower material strengths than the Earth space elevator, which will require carbon nanotubes (shown in Table 1 for comparison). All these materials, save the carbon nanotubes, are available now.

Table 1. Candidate Materials for LSE Compared with Carbon Nanotubes

Material	Density ρ, kg/m^3	Stress Limit σ, GPa	Breaking height $h = \sigma/\rho g$, km
SWCN*	2266	50	2200
T1000G†	1810	6.4	361
Zylon PBO‡	1560	5.8	379
Spectra 2000¶	970	3.0	316
M5**	1700	5.7 (9.5)	342 (570)
Kevlar 49††	1440	3.6	255

*Single-wall carbon nanotubes (laboratory measurements) †Toray Carbon fiber
‡ Aramid, Ltd. Polybenzoxazole fiber ¶Honeywell extended chain polyethylene fiber
** Magellan honeycomb polymer (with planned values) †† DuPont Aramid fiber

The design of the lunar space elevator ribbon can be made more robust and fail-safe by using multiple ribbons with alternate load paths, after Forward and Hoyt[11]. The concept is shown in Figure 7, with a table of the required safety factor vs. the number of ribbons. The lifetime of the LSE can be estimated from the mean time between meteor cuts: T, yrs = 6 $h^{2.6}/L$, where h is the ribbon width in mm and L is the length in km.



Number of Ribbons, n	2	3	4	5	6
Safety Factor, f_0	4	3	2.7	2.5	2.4

Figure 7. Fail-Safe Ribbon Design

Once the minimum base area is set and the taper ratio is known, the total mass of the space elevator can be calculated. For a modern high-strength composite like the Magellan M5, the total system mass is shown in Figure 8. The mass is plotted vs. the length of the space elevator, from the surface to a point beyond L1, where it is terminated by a counterweight that keeps it in balance while it lifts loads at the surface. The CW must equal in weight the entire length of the ribbon below L1; its weight is zero at L1, where it is balanced in orbit, and rises linearly with distance above L1. If the ribbon extends to infinity, no counterweight is required. This gives the very interesting paradox that the longer the space elevator, the less the total weight, although the amount of high-strength ribbon goes up. The counterweight can be inert lunar regolith material, or even a space station.

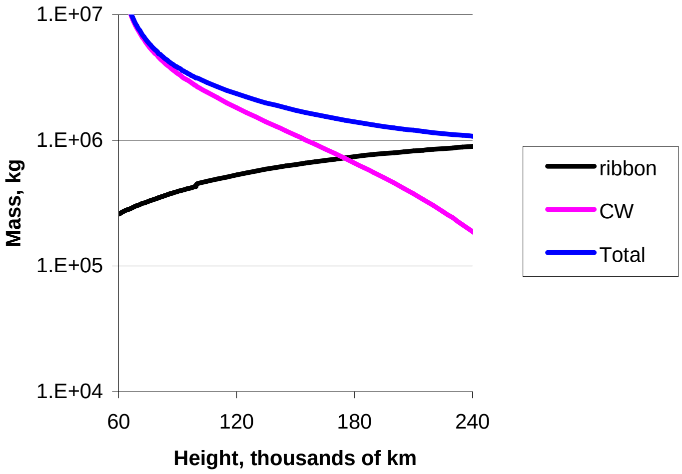


Figure 8. Mass of the LSE Ribbon and Counterweight for Different Lengths

The analysis of lunar space elevators by Levin[12] is the basis for these results. The L1 point is only about 58,000 km from the center of the Moon, but there are two advantages to making lunar space elevator extend far beyond this point. The first is the drastic reduction in the mass of the CW, and therefore the total mass that must be lifted from the Moon to L1 for its construction. The second is the fact that payloads released from the top of the LSE drop into elliptical Earth orbits whose perigees will be lower the longer the LSE is. Figure 9 shows this effect. If the LSE reaches 130,000 km, payloads will have perigees at GEO; 180,000 km puts them in MEO, and releasing at 240,000 km would cause them to enter the atmosphere. Because the tram vehicles have plenty of electric power, they could use electrodynamic propulsion to circularize their orbits if the perigee is below about 8000 km radius. Conversely,

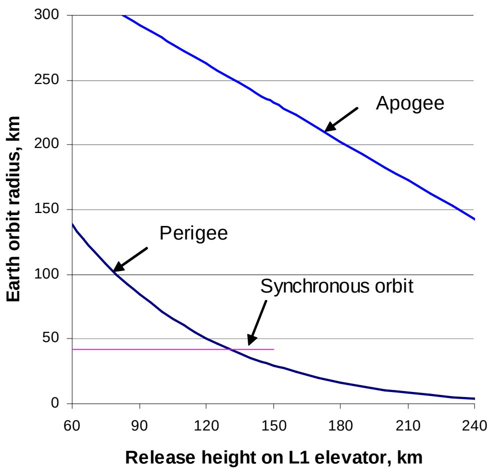
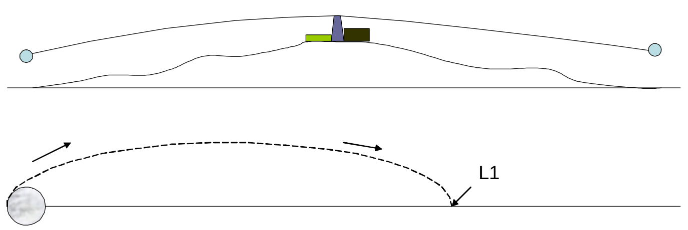


Figure 9. Earth Orbit after Release

electrodynamic propulsion vehicles leaving LEO to carry payloads to the Moon could propel themselves to the top of the LSE without rockets if the top were about 210,000 km from the Moon. For these important reasons, the lunar space elevator should be perhaps up to 200,000 km long; this will require 400,000 kg of ballast material, typically lunar regolith, in addition to the 800,000 kg of high-strength composite. The conceptually simplest way to send this material to the L1 position is with a mass driver.

Arthur Clarke[13] suggested electromagnetic launching in 1950, and the concept of the electromagnetic mass driver was revived[14] in the 1970's. However, this design requires high power, high precision, and lots of material to be shipped from Earth for its construction. A simpler system would be a rotating sling launcher after Heppenheimer[15], Levin[12], and Landis[16], using the same high-strength material as the lunar space elevator. Emplacing such a sling near the lunar north pole on a high point in nearly constant sunlight would allow the use of solar power to rotate the system, with dual payloads at the ends. The concept is shown in Figure 10, based on the Levin analysis. The power station and sling tower are on a mountain top, and the cables are extended as the rotational velocity rises to the launch velocity.

For 100 kW of total power, the tip velocity could reach 2.38 km/sec, enough to reach escape (or L1), at a length or 236 km, and the system could launch 3 tons per day to L1. The lunar sling could launch both regolith counterweight and high-strength ribbon material into L1, from which the lunar space elevator could be extended until the bottom touched the ground. The LSE could then support climbers to lift additional materials.



Type	h, km	r, km	V_{tip}, km/s	a_{tip}, g's	P, kW	Tons/day
Low Orbit	4	118	1.68	2.4	100	3
Escape	4	236	2.38	2.4	100	3

Figure 10. Lunar Sling Launcher

4. Lunar Tramway and Cable Cars

The lunar tramway component must extend from the equator to the pole, about 2700 km. There is a trade-off between the height of the towers and the span, as shown in Figure 11. The ground clearance height is shown vs. the latitude span for support towers of 1, 2, and 3 km height. The 1-km towers allow spans over level ground of at least 3 degrees, or about 90 km. This would require only 30 towers between the equator and the pole. If the tramway takes advantage of topography, it would require even fewer towers. Towers of 2 or 3 km would reduce the number required to

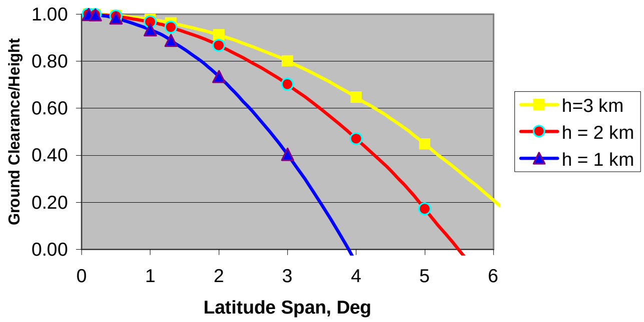


Figure 11. Tower Span vs. Height

20 or even 16, but their greater height might cause problems in construction and stability. Building 1-km towers on the Moon is like building 160-meter towers on the Earth, and they can be very light if made of modern composite designs, such as that shown in Figure 12.

One method for reducing the overall cost of the lunar space elevator is to use *in situ* lunar materials to make fibers that are strong enough to reinforce the initial ribbon. This could greatly increase the carrying capacity of the LSE, and also greatly reduce the amount of material that must be lifted out of the Earth's gravity well.

Lunar aluminum, silicon, iron and titanium are abundant. Aluminum has a relatively low density, and can be used to create high strength fibers. Its strongest form seems to be sapphire, which can be grown as long single crystals or whiskers. The processes involved might even benefit from the microgravity environment at L1. Perhaps we could grow continuous crystal strands that could go directly into the ribbon assembler. Sapphire whiskers are almost as strong as graphite whiskers, although they are more than twice as heavy.

Another material which compares favorably is quartz whisker. Silicon is plentiful and if we can generate whiskers in space they would be many times stronger than glass fibers made from the same element. Fibers in a metal matrix are also currently popular, and an application might be sapphire whiskers in glassy aluminum foil. Glass fibers with metal coatings might be used, since there is no water or oxygen problem.

Figure 12. Lightweight Composite Towers

5. Lunar Highways, Vehicles, and Service Stations

The construction of the lunar tramway will require that service vehicles travel over the length of the system, and they will need a good surface to travel on. It is possible that the vehicles that erect the support towers could also smooth or pave a road on which ground vehicles could travel. Taylor and Meek of UT Knoxville developed a method[17] for using microwaves to sinter lunar regolith into a hard, smooth surface like a paved road. Figure 13 shows a sketch of their microwave paving machine. It would have two sets of magnetrons that can be set to various microwave frequencies and power in order to effectively sinter/melt the lunar soil. The first set would sinter the regolith to a depth of about half a meter, and the second set would melt the top 3-5 cm to create a hard, smooth road surface. The microwave process would release most of the solar wind particles imbedded in the regolith, notably hydrogen, helium, carbon, and nitrogen, which might be captured for other uses. This could be very valuable in solving the problem of lunar dust, which has proven to be very

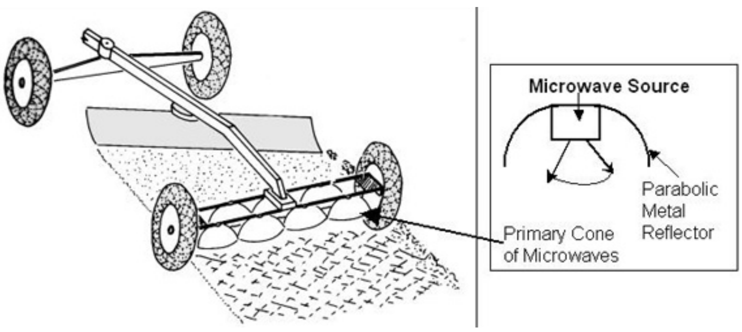


Figure 13. Lunar Microwave Paving Machine

difficult to deal with. In building the lunar tramway, we could also end up with a lunar highway for surface vehicles.

This leads into the problem of powering vehicles, whether tramway capsules or robotic ground vehicles, or eventually manned vehicles, over long distances during the lunar night. The Apollo rovers used silver-zinc batteries with storage efficiency of about 130 W·hr/kg, and achieved ranges over "dirt roads" of about 50 km[18]. More efficient storage systems, whether advanced rechargeable batteries such as lithium ion at 350 W·hr/kg, or hydrogen/oxygen fuel cells at 650 W·hr/kg, could raise the range considerably, as shown in Figure 14.

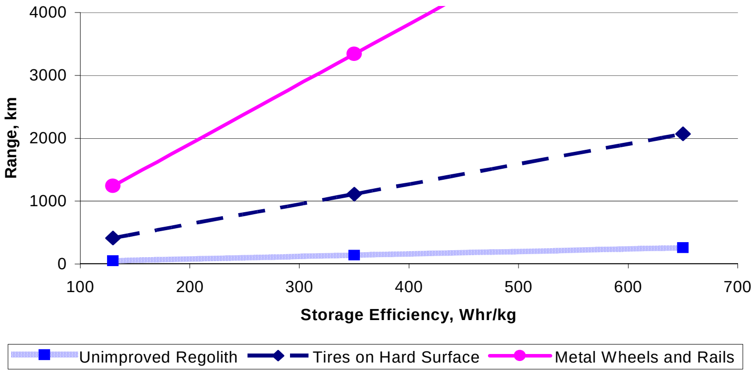


Figure 14. Surface Vehicle Range vs. Storage Efficiency

More importantly, the rolling resistance of wheels on the lunar regolith can be greatly reduced by preparing the surface. The hatched line on Figure 14 represents the Apollo lunar roving vehicles—flexible aluminum tires on unimproved regolith. The dashed line represents the rolling resistance of typical tires on concrete, which might be achieved by treating the regolith with microwaves. Finally, the solid line represents the ranges that could be achieved with metal wheels and rails, like typical railroads on Earth. These three cases represent coefficients of rolling resistance of 0.12, 0.015, and 0.005, respectively.

The best we can do with unimproved regolith is perhaps 300 km of range. That would require about 9 service centers spread over the 2700 km from the pole to the equator. By microwave treatment of the regolith, we might achieve up to 2000 km of range, requiring only one service station, in the middle of the trip. If we could create a lunar railroad, however, with solid metal-wheeled vehicles and metal rails, then we could achieve pole-to-equator range during the lunar night, and not require service stops along the way at all, except perhaps as a backup for vehicle failures. The capsules traveling on the lunar tramway should be roughly equivalent to metal wheels on metal rail, and would not need to stop during the long lunar night. At a speed of 30 m/s, the tramway capsules could cover the entire distance in just 25 hours.

Even if service stations are required for the ground vehicles, they could be automated to charge enough batteries by solar power during the lunar day to provide charged batteries for many vehicles during each night. If required, an occasional vehicle could drop off extra batteries, leaving sufficient numbers of charged batteries each lunar night. With parallel tracks, or even occasional "passing tracks," the system could provide continuous two-way traffic.

6. Advanced System Operations

The system of robotic vehicles on tramway, roadway, and space elevator might be able to function nearly autonomously, carrying multiple vehicles both ways. Robotic attendants at the equator, pole, and central service station might be all that is required to keep operations smooth.

There are some possible advanced methods to improve the operation of the lunar space elevator. Building a tall tower at the base of the space elevator, creating a space elevator partly in tension and partly in compression[19] would reduce the taper ratio required, resulting in much lower mass and less counterweight. Curving the lower end of the elevator ribbon to touch down away from the equator is not an improvement; although it lowers the number of towers required to reach the pole, it drastically reduces the payload capacity of the elevator ribbon. Reaching just 15 degrees of latitude reduces the carrying capacity by 25%.

Finally, it may be possible eventually to use the tramway ribbon itself to carry electrical power along its length, allowing capsules to draw power continuously through the night. Other, less likely, methods are to beam power to spots on the tramway from solar power stations at the equator, the poles, and perhaps even in low lunar orbit.

7. Conclusions

The integrated lunar transportation system is a complete non-rocket transportation system for carrying lunar resources to Earth orbit and for carrying manufactured goods from Earth orbit to the lunar poles. It depends on high power from solar arrays, electric motors for propulsion along the tramway and space elevator, and electric rockets for the free-flight leg between the top of the lunar space elevator and Earth orbit. If the Earth space elevator is ever built, the system could provide two-way cargo transportation from the surface of the Earth to the surface of the Moon.

Acknowledgments

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